# POLICY PRIMER: WHAT IS THE NUCLEAR-CLIMATE NEXUS?

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# Policy Primer: What is the Nuclear-Climate Nexus?

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## Background:

This report includes a collection of annotations to provide policy practitioners and subject matter experts (SMEs) a literature overview of the nexus between nuclear and climate issues. This report broadly responds to policymaker questions concerning the challenges and opportunities for the nuclear nonproliferation mission amid climate change threats. Nuclear SMEs and climate change SMEs are often stovepiped in organizations, and therefore, this report is meant to prompt conversations between the two groups and to help them understand the overlapping aspects of nuclear and climate change issues. Questions nestled in between the nuclear and climate nexus include:

- What are vulnerabilities of existing and future nuclear infrastructure due to the impacts of climate change?
- Which new nuclear technologies are needed to help countries reach net-zero emissions goals, and what are associated concerns with safety, security, safeguards, and export controls?
- Is our current international governance structure fit to effectively address new legal, regulatory, and governance challenges that might arise due to the expansion of nuclear energy globally?
- How can we leverage monitoring technology developed for climate research for nuclear verification and monitoring, and vice versa?
- What are second order effects of climate change that might affect the nuclear industry?

[1] *The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.*

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## Assessing Nuclear Infrastructure Resiliency

- How might climate change (e.g., water stress, extreme weather, permafrost thaw, etc.) affect the (land/facility/material) resilience of nuclear infrastructure?
- How should climate-related infrastructure risk be considered when adapting and building new sites?
- The global expansion of civil nuclear power will accelerate the spread of dual-use technology and knowledge and increase overall demands on safety, security, safeguards, and export controls. How should we adapt?

OECD/NEA, "Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Approaches for their Adaptation," *Nuclear Development.* Paris: OECD Publishing (2021). https://doi.org/10.1787/cdb52aed-en.

> The study concludes that the main risk to nuclear power plants due to climate change impacts relates to water, "due to intense flooding or a lack of water for cooling." Droughts, heat waves, and high-water temperatures can affect cooling water availability and quality. When needed, the cooling systems of existing nuclear power plants can be retrofitted to reduce water withdrawal or decrease the cooling system's temperature sensitivity. New power plants can be constructed with closed-cycle cooling to reduce water intake. Building new nuclear power plants along the coast, rather than at river sites, reduces temperature-related vulnerability, but this may increase vulnerability to sea-level rise and flooding. While the study finds that extreme weather events like floods, storms, frazil ice, and forest fires can undermine nuclear power plant operations and safety, it states that in general nuclear power plants are resilient infrastructure.

Liou, Joanne, "IAEA Collaborating on Notification System to Protect Nuclear Installations from Natural Hazards," IAEA News Center (October 1, 2021). https://www.iaea.org/newscenter/news/iaea-collaborating-on-notification-system-to-protect-nuclear-installations-from-natural-hazards.

> The International Atomic Energy Agency (IAEA) is creating the External Events Notification System (EENS) to monitor and respond to natural hazards that could impact nuclear installations worldwide. These hazards, which include floods, earthquakes, volcanic eruptions, wildfires, and more, are increasing in frequency and intensity due to climate change. Developed in collaboration with the University of Hawaii's Pacific Disaster Center (PDC) and the internet application developer Tenefit, the EENS will be based on PDC's DisasterAWARE system, providing real-time hazard monitoring and early warnings. It will consist of two modules: an Alert System, which will monitor global hazards and trigger alerts, and an External Event Damage Forecast, which will estimate the impact on nuclear facilities and populated areas. Reports will be sent to the IAEA's

Incident and Emergency Centre (IEC) within 30 minutes, enabling timely response and support to affected countries.

"Climate Change and Nuclear Power 2022: Securing Clean Energy for Climate Resilience," International Atomic Energy Agency (2022). https://www.iaea.org/sites/default/files/iaea-ccnp2022-body-web.pdf.

Global energy infrastructure will be increasingly exposed to frequent and severe climate hazards that could impede the reliability of nuclear plants and timely achievement of carbon neutrality. Chapter four highlights key trends in climate, weather, and water risks that must be considered during siting and design of new nuclear installations and stress tests for evaluating safety margins for existing facilities. Adaptations that combine engineering provisions with operation and performance-related procedures can be made to ensure robustness and climate resilience. New predictive tools, rather than historical data, will help to anticipate weather and water-related events and mitigate economic and societal impacts. Chapter five takes stock of some of the key economic and environmental characteristics in the Middle East and Africa, provides some rationale to nuclear developments in the region, and outlines some of the barriers to deployment in the near term.

Choromokos, Rob, et al, "Climate Vulnerability Assessment Guidance for Nuclear Power Plants," EPRI (November 16, 2022). https://www.epri.com/research/programs/061177/results/3002023814.

While extreme weather events have had minimal impact on nuclear capacity factors thus far, stakeholders must recognize that the design standards for existing plants reflect an intensity and frequency of extreme weather events at the time of their licensing. This technical report provides guidance for conducting forward-looking vulnerability assessments of nuclear power plants (NPPs) based on the projected challenges of climate change impacts. The guidance recommends conducting screening of all structures, systems, and components important to the design of the plant and evaluating if any are vulnerable to climate change impacts. Conducting specific vulnerability analyses for assets and systems will optimize the future selection, design, installation, operation, and refurbishment of NPPs in a reliable, resilient, responsible, and cost-effective manner.

## Next-Generation Nuclear Technologies

- How will growing demand for low-carbon energy (due to climate change) and expanded applications of nuclear technology impact next-generation nuclear energy technologies, and their safety, security, and export controls?
- How can next-generation nuclear technologies increase the U.S. nuclear energy industry's global competitiveness?
- How do these advancements impact how we are approaching safeguards, non-proliferation, and arms control?

National Academies of Sciences, Engineering, and Medicine, "Laying the Foundation for New and Advanced Nuclear Reactors in the United States," Washington, DC: National Academies Press (2023). https://nap.nationalacademies.org/catalog/26630/laying-the-foundation-for-new-and-advanced-nuclear-reactors-in-the-united-states.

> There are several new advanced reactors being developed—including small modular light water reactors, reactors that use non-water coolants, and those that use higher levels of enriched uranium. These reactors are meant to increase safety, reduce costs, increase thermal efficiency, increase flexibility, and/or reduce the need for water. In terms of safety and operational advantages, advanced reactors are likely to incorporate extensive use of digital controls, advanced sensors, and data science capabilities. Developers of these advanced reactors will need to demonstrate that their designs meet regulatory standards specifically being developed for advanced reactors. Developers will also face the challenge of ensuring these reactors are economically viable.

Karan, Mistry, Tina Zuzek-Arden, Thomas Baker, and Emma Delrose, "Potential for US Competitiveness in Emerging Clean Technologies," *Boston Consulting Group* (September 2022): 1–87. https://web-assets.bcg.com/fc/d4/9a39f69141d9aab29f41900712ad/how-the-us-can-win-in-six-key-clean-technologies-r.pdf.

> The study finds the United States has an opportunity to lead in the deployment and exports of advanced nuclear small modular reactors (SMRs) because of its early lead in intellectual property and research and development (R&D), its strong regulatory institutions, and large number of private market participants. Constraints to U.S. leadership include the lack of domestic commercial development of high-assay low-enriched uranium (HALEU) fuel required for SMRs, and different regulations in various countries might impede exports. The authors recommend the United States build domestic HALEU production capacity, source uranium supply via allies (like Canada and Australia), and harmonize nuclear regulations with priority export markets to give U.S. companies an advantage. The study forecasts that about 180-220 gigawatts (GW) of SMRs will be deployed worldwide through 2050.

Nakano, Jane, “The United States Looks to Fusion to Re-Inject Energy in the Global Climate Efforts,” Center for Strategic and International Studies (December 8, 2023). https://www.csis.org/analysis/united-states-looks-fusion-re-inject-energy-global-climate-efforts.

> There are over 40 companies globally working to develop nuclear fusion, attracting $6.2 billion in investments. Of those 40 companies, 25 are headquartered in the United States. The United States is pushing for more international cooperation on fusion development, including on R&D, global market development, regulatory frameworks, workforce, and public education on fusion. Since December 2022, the National Ignition Facility at the Lawrence Livermore National Laboratory twice achieved net energy gain from fusion reactions. The main benefit of fusion energy includes producing four times more energy per kilogram of fuel than traditional NPPs running on nuclear fission, and it is considered to be much safer.

Ashton, Lucy, “Embracing the Promise of Additive Manufacturing for Advanced Nuclear Reactors,” *IAEA Bulletin* 64, no. 3 (September 2023): 14–15. https://www.iaea.org/bulletin/64-3.

> Companies and institutions are testing 3D printing in hopes that it will accelerate the future deployment of advanced reactors. Experts believe 3D printing could potentially reduce manufacturing costs for the nuclear industry by increasing manufacturing speed, reducing waste, and reducing the weight of objects. There have been a few use-cases, including a 3D-printed pump impeller installed at a Slovenian reactor, printed brackets called channel fasteners installed in a nuclear power reactor by Oak Ridge National Laboratory, a 3D-printed, stainless steel fuel component at the Forsmark nuclear power plant in Sweden, and other 3D uses cases in Russia and South Korea. In Europe, the Nuclear Components Based on Additive Manufacturing (NUCOBAM) project is aiming to develop the qualification and evaluation process that would allow 3D printing to be used in NPPs. In the United States, DOE and the Electric Power Research Institute are researching regulatory considerations.

Jenner, Edward, “Combating Climate Change While Promoting Nonproliferation: Addressing New Challenges,” Center for Global Security Research at Lawrence Livermore National Laboratory (September 15, 2022). https://cgsr.llnl.gov/content/assets/docs/SMR-FNPP-Risk_9.15.22_EJ_FINAL.pdf.

> While novel SMR designs seek to improve upon safety with passive safety features to mitigate nuclear accidents, novel systems and designs can pose novel risks. SMRs require HALEU fuel, which has been enriched to somewhere between 5% and 20%, above standard NPPs, which operate generally at or below 5% enrichment. Countries will potentially have a lower barrier to pursue nuclear weapons with HALEU, though SMR designs with a sealable core can mitigate this. FNPPs pose inherent safety, security, and safeguards risks, and introduce maritime concerns, such as the risk of collision or sinking.

If SMRs and FNPPs grow in popularity, then there could be comparatively more locations with nuclear material than if traditional larger NPPs were utilized. This could burden the safeguards regime as there would be more monitoring required.

## Evolving Nuclear Landscape and Nuclear Non-Proliferation, Governance Gaps

- How can existing organizations and regimes (e.g., the IAEA, Nuclear Suppliers Group-NSG) evolve to meet challenges to safety, security, and non-proliferation stemming from rising demand for nuclear energy for decarbonization?
- Where will we see challenges to implementing IAEA activities? Will the IAEA be stretched too thin? If so, in what areas?
- Are there other organizations or regimes that would complement existing organizations and regimes in anticipation of the evolving nuclear landscape?
- Domestically, how can U.S. regulatory frameworks address these risks (e.g., civil nuclear cooperation, export controls, supply agreements, etc.)?

Varrall, Suzanne, "The Next Nuclear Wave: Renaissance or Proliferation Risk?" *Global Change, Peace & Security* 24, no. 1 (February 1, 2012): 127–40. https://doi.org/10.1080/14781158.2012.641293.

The author believes that growing interest in nuclear energy worldwide does present a real proliferation challenge, and the mere possession of civil nuclear capabilities lowers barriers of technology and expertise to future weaponization. The author, however, notes that those risks can be mitigated through confidence-building measures and security guarantees to remove any perceived need for nuclear deterrence as a hedging strategy. To meet this burden, the IAEA must be strengthened through increased funding and more extensive legal authority. The author also recommends non-nuclear weapons states sign an agreement not to own or operate fuel development and reprocessing capabilities for their civilian nuclear power industry.

Miller, Nicholas, "Why Nuclear Energy Programs Rarely Lead to Proliferation," *International Security* 42, no. 2 (November 1, 2017): 40–77. https://doi.org/10.1162/ISEC_a_00293.

The author argues that countries with nuclear energy programs are not more likely to pursue nuclear weapons, contrary to conventional wisdom. He asserts that countervailing mechanisms and political restraints reduce the odds that countries with civilian programs will proliferate. These countervailing mechanisms include the fact that civilian programs attract attention and non-proliferation pressure, and secondly, the potential costs of nonproliferation sanctions targeting nuclear fuel supplies and technologies, which are needed to run the civilian program. The author provides an historical, empirical assessment showing that states with nuclear energy programs have not been significantly more likely to pursue nuclear weapons, but the study excludes countries with research reactors.

Kim, Sung Chull, “Endangering Alliance or Risking Proliferation?: US–Japan and US–Korea Nuclear Energy Cooperation Agreements,” *The Pacific Review* 30, no. 5 (September 3, 2017): 692–709. https://doi.org/10.1080/09512748.2017.1293715.

This paper examines the sensitive issue of granting enrichment and reprocessing (ENR) rights by investigating the divergent approaches taken by the United States in revising bilateral nuclear cooperation agreements with Japan and South Korea. Two key factors shape U.S. decisions as a supplier state: first, policymakers’ apprehension about alliance management, considered prior to assessing security outcomes, and second, the impact of commercial interests held by relevant firms. ENR rights were extended to Tokyo to safeguard the U.S.–Japan alliance and maintain Japanese support for the American nuclear industry. Conversely, the United States refrained from granting ENR rights to South Korea, primarily due to its confidence in managing the U.S.–Korea alliance and an incongruity in commercial interests between the allies. This comparative analysis challenges prevailing nuclear proliferation theories, emphasizing alliance management as an antecedent element of power projection, and highlighting factors such as fuel sales and technological partnerships in shaping nuclear cooperation agreements.

Ford, Michael J., Ahmed Abdulla, and M. Granger Morgan, “Evaluating the Cost, Safety, and Proliferation Risks of Small Floating Nuclear Reactors,” *Risk Analysis: An Official Publication of the Society for Risk Analysis* 37, no. 11 (November 2017): 2191–2211. https://doi.org/10.1111/risa.12756.

This paper evaluates the cost, safety, and proliferation risks of the build-own-operate-return (BOOR) model, in which small modular reactors are produced in a factory and deployed to a customer nation on floating platforms, owned and operated by a single entity, and returned for refueling and waste processing. The authors assert that returning small land-based reactors containing spent fuel is infeasible, and therefore, recommend placing them on floating platforms. The authors develop a decision model considering key IAEA plant-siting criteria to compare this approach to traditional land-based solutions. Their findings suggest that, depending on the specification requirements of a floating nuclear power plant, the BOOR model may be a cost-effective solution and should reduce the material proliferation risk.

Wang, Qiuwen, Yan Zhang, and Hu Zhang, “The Development of Floating Nuclear Power Platforms: Special Marine Environmental Risks, Existing Regulatory Dilemmas, and Potential Solutions,” *Sustainability* 15:4 (February 2023). https://doi.org/10.3390/su15043022.

Floating nuclear power plants (FNPPs) can provide clean energy supply for remote islands and offshore platforms at potentially lower costs, but FNPPs present governance, regulatory, and environmental challenges. Although there is no specialized regulatory convention for FNPPs, the authors list several international conventions, protocols, and resolutions that might involve the regulation of FNPPs and their related marine environmental issues—including the 1982 United Nations Convention on the Law of the Sea and conventions, protocols, and resolutions adopted under the International Maritime Organization and the IAEA. The authors argue existing regulatory frameworks fall short of addressing the jurisdictional, nuclear safety, and environmental challenges posed by FNPPs and recommend new frameworks or updates to existing ones. Currently, Russia is the only country with an operational FNPP, and China plans to deploy 20 FNPPs in the South China Sea.

## Identifying and Leveraging Verification and Monitoring Technologies

- Which technologies (e.g., instrumentation, data analysis techniques, etc.) currently being developed or used as part of climate science R&D could be leveraged for strengthening the non-proliferation monitoring and verification regime?
- How can data from treaty verification (non-proliferation and arms control research) enrich climate science research?
- How do existing verification and monitoring technologies need to change to accommodate new nuclear technologies?
- How will climate change affect reliance on existing technology?

Edwards, Paul. "Entangled Histories: Climate Science and Nuclear Weapons Research," *Bulletin of the Atomic Scientists* 68, no. 4 (July 1, 2012): 28–40. https://doi.org/10.1177/0096340212451574.

This paper summarizes the intimate historical relationship between climate science and nuclear weapons research. The earliest atmospheric transport models were built between 1955 and 1965 to analyze nuclear blast shockwave propagation through the atmosphere. These models directly informed early climate models, which depend on an accurate understanding of how particles and gases propagate and circulate around the world. One reason sophisticated transport models are so critical for understanding climate change is that greenhouse gases and particulate matter have opposite effects on global warming; greenhouse gases retain heat while particulate matter tends to reflect sunlight and reduce heat retention in the atmosphere. The climate models that early nuclear weapons research made possible improved our understanding of the climatic consequences of atmospheric nuclear testing and of a potential nuclear war. They showed that the consequences of atmospheric nuclear explosions are global because the radioactive material and particulate pollution they produce are not confined to the immediate blast area.

"The Nuclear Test-Ban Verification Regime: An Untapped Source for Climate Change Monitoring." Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (2008). https://www.ctbto.org/sites/default/files/Documents/01122008_climate_change_final_web.pdf.

> The Comprehensive Nuclear-Test-Ban Treaty (CTBT) establishes a verification regime designed to detect clandestine nuclear tests anywhere on Earth. An important component of this regime is the International Monitoring System (IMS), which consists of 337 facilities that monitor the entire world. The IMS is sophisticated with high bandwidth; its sensors transmit data continuously to a central hub in Vienna where it is analyzed and distributed to member states. Some of the data these sensors collect are climate-relevant and not collected by most meteorological sensors (e.g., infrasound and radionuclides). The ability to track radioactive particles is particularly important because studying their movement allows for better modeling of atmospheric transport. Accurate atmospheric transport models are important for understanding how greenhouse gases and other pollutants travel through the atmosphere and affect climate. The IMS also has the bandwidth capacity to transmit additional data for climate change monitoring if more sensors are added in the future.

Multiple Authors, "Book of Abstracts. CTBT: Science and Technology Conference 2023," Vienna: Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (2023). https://conferences.ctbto.org/event/23/book-of-abstracts.pdf.

> This book is a lengthy series of research abstracts on the science and technology underlying the CTBT's verification system. One body of research focuses on the various ways in which the data collected by the International Monitoring System (IMS) sensors can be leveraged to better understand earth sciences. Applications range from studying atmospheric transport models important for climate change research to using acoustic vibrations to study geological phenomena like earthquakes and volcanos. A second body of research examines ways to improve methods for detecting nuclear detonations. Many of these methods relate to distinguishing seismic vibrations from underground nuclear tests from other seismic events or distinguishing radioactive isotopes from atmospheric nuclear explosions from those produced by other phenomena.

Eslinger, Paul, et al. "Impacts of future nuclear power generation on the international monitoring system," *Journal of Environmental Radioactivity* 273 (March 2024). https://doi.org/10.1016/j.jenvrad.2024.107383.

> The detection of radioxenon isotopes is often the only method capable of distinguishing a nuclear explosion from a chemical one. While nuclear explosions create many radioactive isotopes, radioxenon is unique in that it is chemically stable in the atmosphere and can therefore reliably travel the distance between a nuclear blast and IMS sensors. However, radioxenon is also emitted by civilian nuclear power plants,

which makes it difficult to determine whether a radioxenon detection is from a nuclear explosion or a civilian facility. This difficulty will become substantially greater if, as some analysts predict, civilian nuclear power generation more than doubles by 2050. In this scenario, current capacity to process and interpret radioxenon detections would be significantly strained. Addressing this problem requires developing better automated methods for discriminating between radioactive xenon released from industrial sources and nuclear explosions.

## Second Order Effects of Climate Change on the Climate – Nuclear Nexus

- What are second order effects of climate change (e.g., geopolitical discord, regional stability, Arctic competition, etc.) that might affect the nuclear industry?
- How can we approach examining and analyzing these second order effects?

National Intelligence Council, "National Intelligence Estimate: Climate Change and International Responses Increasing Challenges to US National Security Through 2040," Washington, DC: Office of the Director of National Intelligence (2021). https://www.dni.gov/files/ODNI/documents/assessments/NIE_Climate_Change_and_National_Security.pdf.

This report asserts that geopolitical tensions are likely to grow as countries increasingly argue about how to accelerate the reductions in net greenhouse gas emissions that will be needed to meet the Paris Agreement. Debate will center on who bears more responsibility to act and to pay—and how quickly—and countries will compete to control resources and dominate new technologies needed for the clean energy transition. The increasing physical effects of climate change are likely to exacerbate cross-border geopolitical flashpoints as states take steps to secure their interests. Scientific forecasts indicate that intensifying physical effects of climate change in 2040 and beyond will be most acutely felt in developing countries, which are also estimated to be the least able to adapt to such changes. These physical effects will increase the potential for instability and possibly internal conflict in these countries, in some cases creating additional demands on U.S. diplomatic, economic, humanitarian, and military resources.

Dolgin, Elie, "Water and warfare: the battle to control a precious resource," *Nature Sustain* 6 (December 2023): 578–586. https://doi.org/10.1038/d41586-023-03883-w.

This article examines how climate change could intensify the role of water—a vital and strategic asset—in armed conflict, driven by escalating tensions and intensified hostilities. Various examples convey that water resources can be casualties of violence, disputes over water control can act as triggers of unrest, and that water is frequently weaponized. Mounting stresses on water systems from population growth and climate change, and the expected growth of violence and instability, results in an urgent need for comprehensive and cooperative efforts to safeguard water resources and promote peace.

Shepherd, Theodore, Emily Boyd, Raphael Calel, et al, "Storylines: an alternative approach to representing uncertainty in physical aspects of climate change," *Climatic Change* 151 (November 2018): 555–571. https://doi.org/10.1007/s10584-018-2317-9.

This article emphasizes that as climate change research becomes increasingly applied, the need for actionable information is growing rapidly. Representation of uncertainties is a key aspect of climate communication, with current approaches in climate communication being limited. An emerging method is the "storyline" approach, in which emphasis is placed on understanding the driving factors involved, and the plausibility of those factors, to best represent uncertainty in physical aspects of climate change.

Wang, Qiuwen, Hu Zhang, Puxin Zhu, and Jiabei Huang, "Balancing energy security and marine pollution prevention: Legal challenges of utilizing nuclear power for decarbonizing maritime transportation in the Arctic region," *Environmental Science and Pollution Research* (December 2023). https://doi.org/10.1007/s11356-023-31291-0.

Arctic sea ice melt due to climate change opens new opportunities for increased maritime shipping and economic activities in the Arctic. Nuclear-powered vessels (NPVs) and floating nuclear power plants (FNPPs) are seen as ways to decarbonize and support maritime transport and economic activities via the Northern Sea Route (NSR). Russia has the world's largest nuclear icebreaker feet and has been using them to navigate Arctic routes. Russia is also planning to install multiple FNPPs along the NSR. The authors expect increased geopolitical tensions in the Arctic, as "the operation of NPVs and FNPPs often aligns with the deploying state's regional strategy and may be perceived as a move towards regional militarization, enhancing their naval logistics and, in some cases, contributing to military capabilities." In addition, as climate change and sea ice melt increase accessibility of the Arctic, the authors note this will likely increase geopolitical competition among Arctic states for resources, shipping routes, and maritime claims.

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